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Characterisation of agroindustrial solid residues as biofuels and potential application in thermochemical processes

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ABSTRACT

In the present work, selected agroindustrial solid residues from Brazil – biosolids from meat processing wastewater treatment and mixture of sawdust with these biosolids; residues from apple and orange juice industries; sugarcane bagasse; *açaí* kernels (*Euterpe oleracea*) and rice husk – were characterised as solid fuels and an evaluation of their properties, including proximate and ultimate composition, energy content, thermal behaviour, composition and fusibility of the ashes was performed. The lower heating value of the biomasses ranged from 14.31 MJ kg^{-1} to 29.14 MJ kg^{-1}, on a dry and ash free basis (daf), all presenting high volatile matter content, varying between 70.57 wt.% and 85.36 wt.% (daf) what improves the thermochemical conversion of the solids. The fouling and slagging tendency of the ashes was predicted based on the fuel ash composition and on the ash fusibility correlations proposed in the literature, which is important to the project and operation of biomass conversion systems. The potential for application of the Brazilian agroindustrial solid residues studied as alternative energy sources in thermochemical processes has been identified, especially concerning direct combustion for steam generation.

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1. Introduction

According to the EIA's International Energy Outlook (U.S. EIA, 2011), world marketed energy consumption is expected to increase strongly from 2009 through 2035, rising by nearly 50%. Most of the growth occurs in emerging economies outside the Organization for Economic Cooperation and Development (OECD), especially in non-OECD Asia. Total non-OECD energy use increases by 84% in the reference case, compared with a 14% increase in the developed OECD nations.

These projections have sparked interest in the use of many types of biomass as alternative energy sources, and since the biomass is produced by the photosynthetic reduction of carbon dioxide, utilisation of biofuels can essentially be carbon neutral with respect to the build-up of atmospheric greenhouse gases, increasing both the demand for the characterisation of alternative fuels and the proliferation of scientific papers concerned with this subject (Demirbas, 2004a, 2005; Obernberger et al., 2006; Werther et al., 2000).

Brazil has been a world leader in agroenergy for the last decades. The internal offer of energy in Brazil in 2010 was 268.754 million tons of petroleum equivalent. Renewable sources of energy were responsible for 45.5% of this amount, where 14.0% came from hydraulic and electricity, 9.7% from firewood and charcoal, 17.8% from sugar cane derived products and 4.0% from other renewable sources (Brasil, 2011).

Wood and wood-based materials are also extensively used as fuel for thermal energy generation in the Brazilian industrial sector, particularly in the food industry, which requires large amount of steam. However, the conversion systems still operate at low efficiency. The Brazilian agroindustrial sector produces large amount of residues and by-products which can potentially be used as energy sources. Each year about 330 millions of metrics tons (Mg) of biomass residues are generated in the country. Part of these waste materials is generated from crops, from all sectors of the food industry with everything from meat production to confectionery, such as peelings and scraps from fruit and vegetables, food that does not meet quality control standards, pulp and fibre from sugar and starch extraction, sludges from physicochemical and biological wastewater treatments and filter sludges.

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These residues frequently are not used as energy source because they have poor energy characteristics (low density, low heating value, and high moisture content), causing high costs during transportation, handling, and storage. Some of these drawbacks could be overcome if physicochemical technology was applied to improve physical and chemical properties of biomass residues, for example, they could be densified into briquettes in order to provide more energy per unit of volume, to improve transportation and storage (Felfli et al., 2005a,b; Suárez and Luengo, 2003).

Considering the current application of wood and wood-based materials for thermal energy generation, it becomes easy to promote their mixture with agricultural residues and co-products (when the application of these alone is not feasible, e.g. for technical or environmental constraints) without requiring considerable changes in the process operation when low mass ratios of those are applied. The advantages can be both the reduction in the consumption of primary fuels and the recovering of energy from wastes which would normally be disposed of in landfills and potentially cause environmental problems.

In previously published papers, the authors have studied the combustion application of some biomass fuels in a pilot scale horizontal cyclone combustor in order to evaluate the feasibility for their utilisation as alternative energy sources for steam generation (Floriani et al., 2010; Virmond et al., 2008, 2010, 2011). The influence of the biomass composition on the emissions from combustion was clearly observed, especially considering the N and S contents found in the feedstock and the ash compositions, thus increasing the interest in further evaluating the effects of the biomass properties on thermochemical conversion processes.

Besides energy sources applied to combustion, agroindustrial residues may serve as feedstock for the production of a huge variety of chemical products and liquid fuels via pyrolysis and gasification processes. So far many review papers have focused on green diesel, Fischer–Tropsch fuels, chemicals from glycerol, etc., and on the biorefinery concept: forest residue based biorefinery (Mabee et al., 2005), wheat straw biorefinery (Deswarte et al., 2008), corn biorefinery (Haung et al., 2008). Biomass characterisation is the first step for the development of these processes.

With this background, the aim of this work was to characterise the chemical and physicochemical properties of some Brazilian agroindustrial solid residues, their behaviour under thermal conversion processes, as well as the problems regarding to the ash composition and fusibility in order to assess their potential application as alternative energy sources in thermochemical processes, especially direct combustion for steam generation.

1.1. Biomass properties and effects on thermochemical processes

Biomass presents wide variation in physical and chemical properties, and many publications relate the biomass properties relevant to thermochemical conversion processes, such as presented elsewhere (Demirbas, 2004a, 2005; Jenkins et al., 1998; Van Paasen et al., 2006; Werther et al., 2000; Werther, 2007; Digman et al., 2009).

The high moisture content typically found in biomass fuels can cause ignition and combustion problems, influence the biomass pyrolysis behaviour (the first step of the gasification and combustion processes) and affect the physical properties and the quality of the products (Demirbas, 2004b).

Wood and other plant biomass as well as crop residues are essentially a composite material constructed from oxygen-containing organic polymers. Due to the carbohydrate structure, biomass is highly oxygenated with respect to conventional fossil fuels including hydrocarbon liquids and coals. Typically, 30–40 wt.% of oxygen (O) constitute the biomass sources (on a dry basis, db). The principal constituent of biomass is carbon (C), making up from 30 wt.% to 60 wt.% (db) depending on the ash content. Of the organic components, hydrogen (H) is the third major constituent, comprising typically 5–6 wt.% (db). Nitrogen (N), sulphur (S), and chlorine (Cl) can also be found, usually in quantities lower than 1 wt.% (db), but occasionally well above this. These constituents are directly related to the gaseous emissions of nitrogen oxides (NO_x), sulphur derived compounds (SO_x, H_2S, COS), hydrochloric acid (HCl) and the occurrence of fouling and slagging in thermal conversion systems (Jenkins et al., 1998; Senneca, 2007).

The high reactivity of biomass is a consequence of its physical and chemical characteristics. The volatile content (80–90 wt.%, db) is at least twice that of coals. The H/C and O/C molar ratios range between 1.3–1.5 and 0.5–0.6, respectively. These are higher values than those found for coals, which generally range between 0.8–0.9 and 0.1–0.3 (Encimar et al., 2001).

Compared with most bituminous coals, one of the important features of biomass materials is the presence of significant amounts of alkali and alkaline earth metallic species (mainly K, Na, Mg and Ca), which tend to volatilise during pyrolysis, gasification and combustion, being of important consideration in all aspects of biomass thermochemical conversion. The metal contents also vary amongst biomass sources.

Processing biomass containing different mineral matter compositions may create various problems which can affect the reactor operation or make the thermochemical conversion of biomass in conventional systems unprofitable. Many authors (e.g. Llorente and García, 2005; Pronobis, 2005, 2006; Vamvuka and Zagrafos, 2004) have presented ash fusibility correlations to evaluate the influence of biomass conversion on furnace fouling and wall slagging. The occurrence of these hazards is dependent on the chemical and mineralogical composition of the ash as well as on the conditions in the conversion system (temperature and velocity distribution, reducing or oxidising atmosphere and others).

On considering these correlations, the one proposed by Pronobis (2005) seems to be most compatible with the biomass composition since it considers the influence of several ash constituents:

$$\mathrm{B/A_{(+P)}} = \left[\frac{(\mathrm{Fe_2O_3} + \mathrm{CaO} + \mathrm{MgO} + \mathrm{Na_2O} + \mathrm{K_2O} + \mathrm{P_2O_5})}{(\mathrm{SiO_2} + \mathrm{Al_2O_3} + \mathrm{TiO_2})}\right] \tag{1}$$

The ratio of basic to acid oxides considers the influence of phosphorus as P_2O_5 using (1), and it has been reported that the higher the value of $\mathrm{B/A_{(+P)}}$ the higher the fouling tendency of the ash fraction. The strong fouling tendency of chlorine compounds, when these are present in the biomass composition, leads to a higher amount of this element in the convection surface deposits, which can cause corrosion. The influence of sulphur should also be considered, as proposed by Zygarlicke apud Pronobis (2005) in (2), where S_d is the percentage of S in the dry fuel. If $R_{S(+P)} < 0.6$, the slagging tendency is low; $R_{S(+P)} = 0.6–2.0$, medium; $R_{S(+P)} = 2.0–2.6$, high; $R_{S(+P)} > 2.6$, extremely high.

$$\mathrm{R}_{\mathrm{S}_{(+P)}} = (\mathrm{B/A_{(+P)}}) \cdot S_d \tag{2}$$

In strictly quantitative terms, the values of the above-mentioned fusibility correlation apply only to coal ash, for which there are many examples in the literature. For the thermochemical conversion of the various types of pure biomass, the literature is much sparser and further investigations are required in this research area.

Whilst the volatilisation of the alkali and alkaline earth metallic species may create slagging and/or fouling problems for the operation of gas turbine blades in the gasification-based power generation cycles (Nielsen et al., 2000), the retaining of such species in the char during pyrolysis can provide important catalysts for the char gasification/combustion (Raveendran and Ganesh, 1998; Zolin et al., 2001), helping to reduce the process temperature and thus increasing the overall process efficiency.

In order to obtain acceptable and reusable products, a better understanding is required regarding the series of thermal events which take place during biomass thermal conversion, as this will aid the design and optimisation of practical conversion systems and allow better control of the process (Heikkinen et al., 2004; Zheng and Kozinski, 2000). Relevant information can be obtained by thermogravimetric analysis (TGA/DTG) in a relatively simple and straightforward manner.

Critically related to the biomass properties is the emission of pollutants generated during its conversion, such as polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans (PCDD/PCDF), volatile organic compounds (VOC), NO_x, and SO_2 (Chagger et al., 1998; Kumar et al., 2002; Mckay, 2002; Stanmore, 2004; Watanabe et al., 2004) which must be controlled in order to comply with the stringent limits set by recent legislation.

During combustion the fuel N is mainly converted to gaseous N_2 and NO_x (NO, NO_2). NO_x can be formed via three different reaction pathways: thermal NO_x, prompt NO_x and fuel NO_x formation from the oxidation of fuel N.

Due to the comparatively low furnace temperatures in solid biofuel combustion plants (around 800–1200 °C), thermal and prompt NO_x formations are of minor importance. NO_x formation from the oxidation of fuel N (during a series of elementary reaction steps) is the most important mechanism in biomass combustion units (Obernberger et al., 2006). According to Obernberger apud Obernberger et al. (2006), emission problems (exceeding of emission limits) related to solid biofuels can be expected at fuel N concentrations above 0.6 wt.% (db) and at fuel S concentrations above 0.2 wt.% (db).

Acid gases may also be emitted, such as hydrogen chloride (HCl) if chlorine derived compounds are present in the biofuel composition and others if lead or other metals are present. CO and hydrocarbons, including VOC, are products of incomplete combustion. The reactions between HCl and the products of incomplete combustion (organic compounds) may lead to the formation of highly toxic compounds with potential carcinogenic effect, like PCDD/PCDF, through different mechanisms (Skodras et al., 2007). Monoaromatic compounds like BTEX (benzene, toluene, ethyl-benzene, and o-, m-, and p-xylenes) have high toxicity and are potentially mutagenic or even carcinogenic.

2. Experimental

In this work samples of twelve agroindustrial solid residues were characterised as solid fuels and an evaluation of their properties, including proximate and ultimate composition, energy content, thermal behaviour, composition and fusibility of the ashes was performed. The fouling and slagging tendency of the ashes was predicted based on the fuel ash composition and ash fusibility correlations proposed in the literature.

2.1. Biomass properties

The selected biomasses were organic solid residues originating from the physicochemical treatment of meat processing wastewater (B1, B2 and B3); mixtures of these organic solid residues with sawdust in mass ratios of 3:1, 1:9 and 1:3 (B1SD(3:1), B1SD(1:9) and B3SD(1:3)); apple juice residues (apple bagasse, AB); orange juice residues (OR); sugarcane bagasse (SB); *açaí* kernels (*Euterpe oleracea*, AK) and rice husk (RH).

The three samples of the organic solid residue studied (B1, B2 and B3) were collected from the primary treatment system of a meat processing plant whose activities include the slaughter and processing of poultry and swine, such as previously described by De Sena et al. (2008). The three samples represent replications in time.

The influence of the high N content found in this type of residue on emissions of NO_x during its combustion was noticed in previous studies (e.g. Virmond et al., 2011). One attempt to overcome this problem was to mixture the organic solid residue with sawdust (the main fuel) in different mass ratios to dilute the fuel N and thus reduce the NO_x emissions. Based on that, mixtures of organic solid residues with sawdust in mass ratios of 3:1, 1:9 and 1:3 (B1SD(3:1), B1SD(1:9) and B3SD(1:3)) have been characterised and evaluated comparatively to the pure sludge samples and pure sawdust.

The mixtures B1SD(3:1) and B1SD(1:9) were prepared during the drying process of the B1 and SD biomasses in the referred rotating granulator dryer. The mixture B3SD(1:3) was prepared from the pre-dried B3 and SD samples in another mixer.

Prior to characterisation, the biomass samples were first dried in an industrial rotating granulator drier, which had an operating capacity of 400 kg h^{-1} (model Bruthus, Albrecht, Brazil). The moisture content after drying ranged from 7 wt.% to 20 wt.%, approximately.

The biomass sample of B1 was sent to the Laboratory for Analysis of Solid Fuels, Ash and Deposits, Institute of Combustion and Power Plant Technology (IFK), University of Stuttgart, Germany, for complete characterisation (except thermogravimetry). The proximate analysis of all samples was performed at the Laboratory of Energy and the Environment (LEMA/UFSC). The other analyses were performed in different laboratories in Brazil and the repeatability of the runs was tested.

2.1.1. Proximate and ultimate analyses

Proximate analysis (moisture, volatile matter, ash and fixed carbon contents) was carried out following DIN 51718 (DIN, 2002), DIN 51720 (DIN, 2001) and DIN 51719 (DIN, 1997), respectively. Ultimate analysis (C, H, N, S and O contents) was carried out according to the ASTM D3176 method (ASTM, 1997). The oxygen content was calculated by difference. Chloride was measured using selective ion electrodes (Cole-Parmer) and phosphorus using colorimetric methods.

2.1.2. Heating Value

The higher heating value (HHV) and lower heating value (LHV) were determined by applying the methods ASTM D5865 (ASTM, 2004) and DIN 51900 parts 1 and 3 (DIN, 2000, 2005). The HHV was determined in a calorimeter and the LHV was calculated using the Dulong Eq. (3):

$$LHV = HHV - 2.43 \cdot (9 \cdot H + U) \tag{3}$$

Where the HHV and the LHV are given in MJ kg^{-1}, H corresponds to the mass fraction of hydrogen in the sample determined through the ultimate analysis and U corresponds to the moisture content of the sample determined through the proximate analysis. The samples have been dried before analysis.

2.1.3. Thermogravimetry

Thermogravimetric experiments were performed in order to predict the thermal behaviour of the studied biomasses during the combustion process using mass samples ranging from 2 mg to 12 mg, previously dried, and a TGA-50 instrument (Shimadzu) with a heating rate of 10 °C min^{-1} up to 600 °C, 650 °C or 700 °C, according to the characteristics of each biomass. The samples were kept in the final temperature until the mass loss rate was constant. The mass loss rate was determined in both synthetic air and helium (or nitrogen) atmospheres at a flow rate of 0.5 L min^{-1}.

The ignition behaviour was determined by comparing mass-temperature curves under inert and oxidising conditions. The ignition temperature was taken as the temperature at which the mass loss curves in the oxidation and pyrolysis experiments deviate, such as previously described by Borrego et al. (2009).

As shown in the study by Grotkjær et al. (2003), a number of parameters are known to influence the ignition temperature and ignition mechanism, these include sample mass, particle size (and possibly even geometry), volatile matter yield and oxygen concentration. In addition to these variables a number of system parameters related to the experimental conditions are important in terms of the ignition behaviour.

2.1.4. Ash composition and ash melting behaviour

Ash samples were produced in laboratory using a muffle furnace according to DIN 51719 (DIN, 1997). However, for fuels with high alkali content, as in the case of the biomasses studied, the ash preparation was carried out at 550 °C or 600 °C (it is usually carried out at 815 °C for coals). The composition of the ash samples was determined following the DIN 51729-10 method (DIN, 1996).

The ash melting behaviour of B1 was determined according to the IFK method, which is based on the tests described in ISO 540 (ISO, 1995) and ASTM D1857 (ASTM, 2004). The temperatures of initial deformation, softening, hemispherical and fluid temperatures were determined by measuring the heights of the samples at intervals of 20 °C.

3. Results and discussion

In this section, the properties of the selected biomasses were compared to that of sawdust (SD), taken as reference fuel, due to the fact that wood and wood residues are originally the main fuel applied to steam generation in the Brazilian agroindustrial sector. The properties were then correlated to the characteristics required for the optimal operation of pyrolysis, gasification and combustion processes in order to evaluate their potential application as alternative energy sources. To sustain that, the results obtained by the authors in previous and ongoing research projects on combustion and co-combustion of some of these residues for thermal energy generation were addressed.

3.1. Biomass properties

The properties of the solid fuels studied were presented in the sequence, including proximate and ultimate composition, energy content, thermal behaviour, composition and fusibility of the ashes.

The information obtained from the characterisation of the biomasses studied has been initially applied to evaluating the technical and environmental feasibility of their use as alternative energy sources in thermochemical processes.

3.1.1. Composition of the selected biomasses

Table 1 shows the properties of the biomasses characterised. C, H and O are the main components of solid biofuels, with C and H contributing positively to the higher heating value (HHV). The content of H also influences the lower heating value (LHV) due to the formation of water, and the oxygen content contributes negatively in energetic terms but positively by promoting homogeneous fuel oxygenation, which improves the conversion efficiency.

The lower heating value of the biomasses ranged from 14.31 MJ kg^{-1} to 29.14 MJ kg^{-1} on a dry and ash free basis (daf), all presenting high volatile matter content, varying between 70.57 wt.% and 85.36 wt.% (daf). The volatile matter content determines the facility to ignition and burning of the solids and together with the fixed carbon to volatile matter ratio determines the flame stability during combustion. The higher the volatile matter content, the higher the burning velocity and the lower the flame stability. However, the devolatilisation velocity is also related to the physical structure and to the composition of the biomass particles.

According to De Sena et al. (2008), physicochemical treatment by flotation can generate up to 0.87 kg of organic solid residues per cubic metre (m^3) of treated wastewater in a meat processing industry, and considering that this quantity can vary from 100,000 m^3 day^{-1} to 200,000 of m^3 day^{-1}, the quantity of solids obtained is presumably high (from 8700 kg day^{-1} to 17,400 kg day^{-1}, on a wet basis).

Amongst the organic solid residues obtained from the physicochemical treatment of meat processing wastewater (samples B1, B2 and B3) presented in Table 1, the sample B1 presented the higher contents of C, H and volatile matter compared to the composition of the two other samples. The combination of these factors with the high grease content found in B1 (34.39 wt.%, db) explains its higher energy content. Compared to SD, the LHV (daf) of B1, B2 and B3 samples were approximately 55%, 13% and 37% higher, respectively, which makes these organic residues very attractive as energy sources. Besides some variation inherent to the wastewater treatment process, the composition of the three samples of meat processing industry residues was similar.

According to Obernberger apud Obernberger et al. (2006), emission problems (exceeding of emission limits) related to solid biofuels can be expected at fuel N concentrations above 0.6 wt.% (db). This can occur during the combustion of the majority of the agroindustrial biomasses presented in Table 1, especially the organic solid residues originating from the meat processing industry. The N content found in sample B1 (9.24 wt.%, db) was the highest amongst the biomass samples studied, which can result in high concentration of nitrogen oxides (NO_x) during its combustion. Such assumptions have been observed during the work recently developed by the authors, which comprised combustion tests performed in a pilot scale cyclone combustor applying B1 as sole fuel (Virmond et al., 2011).

Amongst the mixtures of meat processing residues and sawdust studied, the sample B1SD(3:1) presented LHV approximately 75% higher compared to sole SD. Given the high N content originally found inB1, the content of this element in the mixture B1SD(3:1) was ten times the one found in SD (2.10 wt.% and 0.21 wt.%, daf, respectively). The high S content found in this mixture, however, can be attributed to contamination during the blending given that it was higher than the content found in the B1.

The characterisation of the mixture B1SD(1:9), has shown LHV approximately 5% higher compared to SD, not presenting considerable variation in composition in relation to SD, except in terms of the N content, which has increased from 0.21 wt.% to 1.02 wt.% (both daf) with the mixture of SD and B1. Nonetheless, comparing B1SD(1:9) with B1, the reduction of the N content due to the dilution effect increased its energetic exploitation potential for application in co-combustion processes due to the potentially lower emission of NO_x in relation to the burning of sole B1. Additionally, the reduction of the ash content with the mixture would consequently reduce the problems which may arise due to the ashes fusibility behaviour, which will be further discussed in Section 3.1.3 of this report.

The third mixture studied, B3SD(1:3), was prepared with the samples B3 and SD in a mass ratio of (1:3). Such blend has promoted an increase of the LHV of the biofuel by approximately 26% in relation to sole SD whilst noticeably reducing the N content, from 6.75 wt.% (daf) in B3 to 0.99 wt.% (daf) in B3SD(1:3), thus improving even more the fuel properties aiming its use as an alternative energy source for heat and steam generation through combustion.

Evaluating and comparing the three mixtures, it is noticeable the importance of studying the biomass composition and the mass ratio of the blends to have some insights into the potential

Table 1
Biomass properties.

Biomass	B1	B2	B3	B1SD(3:1)	B1SD(1:9)	B3SD(1:3)	SD	SB	AK	OR	AB	RH
Proximate analysis[a]												
Ash, wt.% (db[b])	12.30	8.09	9.15	3.76	1.62	3.05	0.43	0.69	0.87	3.30	2.25	13.43
Volatile matter, wt.% (daf[c])	85.29	79.21	81.68	84.98	80.27	77.56	79.78	82.58	72.58	76.45	85.36	76.19
Fixed carbon, wt.% (daf)	14.71	20.79	18.32	15.02	19.73	22.44	20.22	17.42	27.42	23.55	14.64	23.81
Moisture, wt.% (ar[d])	15.00	16.34	16.34	13.80	19.47	9.80	19.97	9.22	16.53	7.62	8.46	6.89
Ultimate analysis[a]												
C, wt.% (daf)	58.04	41.62	51.59	59.73	55.54	50.43	55.30	45.00	47.41	44.93	53.35	43.14
H, wt.% (daf)	9.01	4.98	8.85	8.68	7.31	6.70	7.14	6.05	6.64	7.10	7.97	5.57
N, wt.% (daf)	9.24	5.60	6.75	2.10	1.02	0.99	0.21	0.30	1.08	1.42	1.75	0.36
S, wt.% (daf)	0.34	0.00	0.00	0.62	0.03	0.00	<0.01	<0.01	0.86	0.14	<0.01	<0.01
O, wt.% (daf)	22.17	47.19	31.20	28.24	35.95	41.58	37.30	48.57	43.73	46.31	36.85	50.91
Cl, wt.% (daf)	0.18	0.05	0.21	0.07	0.05	0.03	0.04	0.05	0.21	<0.01	<0.01	0.02
P, wt.% (daf)	1.03	0.55	1.40	0.56	0.10	0.27	0.01	0.03	0.07	0.09	0.08	n.d.[e]
Heating value[a]												
HHV[f], MJ kg^{-1} (ar)	24.33	18.28	22.41	29.87	18.73	21.71	18.10	15.98	16.82	15.34	22.07	16.50
LHV[g], MJ kg^{-1} (ar)	22.60	17.28	20.66	28.04	17.15	20.29	16.55	14.67	15.38	13.84	20.37	15.44
HHV, MJ kg^{-1} (daf)	27.75	19.89	24.67	31.03	19.03	22.40	18.18	16.09	16.96	15.86	22.58	19.06
LHV, MJ kg^{-1} (daf)	25.77	18.80	22.74	29.14	17.44	20.93	16.62	14.77	15.51	14.31	20.84	17.84

[a] Maximum experimental uncertainties equal to 0.30%.
[b] Dry basis.
[c] Dry and ash free.
[d] As received.
[e] Not determined.
[f] Higher heating value.
[g] Lower heating value.

technical and environmental effects if thermochemical conversion process are to be applied.

Still in Table 1, the results of the characterisation of the plant biomasses (SD, SB, AK, OR, AB and RH) were approximate. The LHV ranged from 14.31 MJ kg^{-1} to 20.84 MJ kg^{-1} (daf), with low ash contents, varying between 0.43 wt.% and 3.30 wt.% (daf), except to RH (13.43 wt.% of ashes, daf) making these biomasses also potentially interesting for application in thermochemical processes. The N concentration found in some of these residues called attention though, especially the samples AK, OR and AB (1.08 wt.%, 1.42 wt.% and 1.75 wt.%, daf, respectively), which may require measures to control the emission of nitrogen derived pollutants during thermochemical conversion. The solid residue generating from the apple juice industry (apple bagasse, AB) presented the highest energy value of this biomass group.

Accordingly to fuel N, all the S present in the fuel will form SO_x emissions during combustion. Plant biomass sources, in general, do not present sulphur in their parental composition, such as observed in Table 1 for sawdust (SD), sugarcane bagasse (SB), apple bagasse (AB) and rice husk (RH). *Açaí* kernels (AK), however, presented the highest sulphur concentration (0.86 wt.%, daf) amongst the twelve biomass samples studied, and orange residues (OR) presented 0.14 wt.% (daf).

The additives applied to meat processing operations, the degradation of proteins as well as the chemicals applied to the physicochemical treatment of the industrial effluent influence the biomass composition. The presence of sulphur in the composition of the organic solid residues from meat industry, for example, can be related to the conversion of sulphur containing proteins as well as to the utilisation of ferric sulphate ($Fe_2(SO_4)_3$) as coagulant agent in the physicochemical wastewater treatment of the industrial effluent. In the particular case of sample B1, a previous study developed by members of the LEMA/UFSC research group resulted in the substitution of the coagulant agent ferric chloride (Fe_2Cl_3) by $Fe_2(SO_4)_3$ in order to make its energetic exploitation feasible (De Sena et al., 2008). Previously, the application of Fe_2Cl_3 resulted in a residue rich in chlorine which could not be applied as energy source as it could result in emission of HCl, dioxins and furans during combustion. Chlorine can also be incorporated to this residue through the use of chlorinated products applied to the cleaning of the industrial installation.

Amongst the biomasses studied, B1, B3 and AK presented the higher concentrations of Cl (0.18 wt.%, 0.21 wt.% and 0.21 wt.%, respectively), which constitute criteria for the selection of the thermochemical process to be applied and require measures during thermochemical conversion not to incur in emission of important pollutants during combustion or gasification, such as HCl. During gasification, Cl can react with available metal compounds present on fly ash which have accumulated on syngas coolers. This can result in local deposits containing up to 15% chlorides such as $FeCl_2$, NaCl, CaCl and causes corrosion other problems downstream (Collot, 2006).

During gasification sulphur originally present in biomass is converted to H_2S which is highly corrosive to syngas coolers and causes serious damage to heat exchange systems as well as having an impact on the cost of sulphur removal and recovery units. Thus, it has been reported to be one of the major properties to take into account for the design of a gasification plant (Collot, 2006).

Considering that the wastewater treatment of a meat processing industry objectives the reduction or the elimination of the pollutant load through physicochemical adsorption and/or biological degradation, the remaining solids can contain organic and inorganic pollutants. Based on that, De Sena et al. (2009) evaluated the presence of the priority pollutants (organic and inorganic) defined by the U.S. EPA in the organic residue originating from this industrial sector. Trace elements, PAH and PCDD/PCDF were identified and quantified. The results proved that these wastes can be safely deposited on land or used in combustion/incineration plants, taking as reference the limits established by the European Union legislation and also by the World Health Organization (WHO).

3.1.2. TGA/DTG trends

The results of TGA/DTG analysis were given as plots of total mass loss (TGA) and mass loss rate (DTG) with temperature, and these were only presented for the samples which have been submitted to combustion tests in previously published works by the authors, i.e., B1 (Virmond et al., 2011), B1SD(1:9) (Floriani et al., 2010; Virmond et al., 2008) and AB (Virmond et al., 2010).

When heated in oxidising atmospheres, solid biomasses lose moisture and volatile compounds, and both homogeneous combustion of volatile matter and heterogeneous combustion of fixed carbon take place. Additionally, mineral matter is oxidised forming ash.

The devolatilisation and oxidation (partial and/or complete) stages may be either simultaneous or successive, such as can be observed in the following figures, depending on the operating conditions. These are also affected by heating rate, pressure, temperature and particle size.

On the DTG curves for SD three distinct peaks are observed, whereas for B1 four peaks appear due to the intrinsic characteristics of each material. The first phase, usually at temperatures below 100 °C, refers to the water release in the case of biomass. The second phase, between 250 °C and 430 °C for SD in Fig. 1, which accounts to approximately 58% of the total mass loss, can be attributed mainly to the thermal degradation of lignocellulosic materials that constitute sawdust and to the release of volatile matter, which mixes easily with oxygen and burns more easily than the fixed carbon. This is a fast burning region, where the mass loss rate reaches its highest value, indicating the peak temperature. The degradation of the residual volatiles and fixed carbon for SD (approximately 30% of the total mass loss) generally occurs from approximately 450 °C to 540 °C. Similar behaviour was observed for the sample B1SD(1:9) (Fig. 3) due to the higher mass ratio of SD in the mixture.

In the burning profile of B1 (Fig. 2), the mass loss observed from around 250 °C to 600 °C can be attributed to the decomposition of different organic compounds, both associated to the grease content (34.39 wt.%, db) and to the volatile matter release, with a total contribution of around 84.4% of the total mass loss (comparable to the volatile matter content obtained through the proximate analysis, 85.29 wt.%, daf). However, the behaviour during the thermal degradation of B1 differs greatly from that observed for SD (Fig. 1), with the fast burning region occurring at higher temperatures. Approximately 24% of the biomass total mass was lost between 520 °C and 600 °C, probably representing the degradation of fixed carbon together with other constituents, mainly volatile matter. It seems that the volatile matter was released gradually during the process until higher temperatures, whilst in SD the volatile matter combustion apparently prevailed as a dominant single step of the combustion process since the highest mass losses were concentrated in intermediate temperature ranges, from 250 °C to 430 °C.

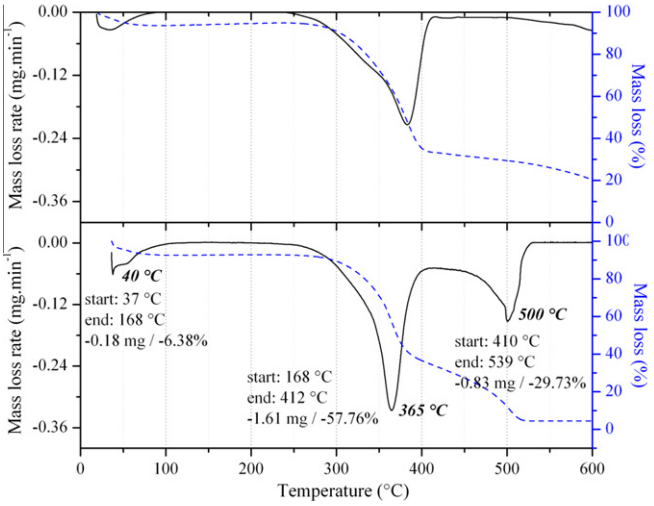

Fig. 1. TGA/DTG profiles of SD in helium (upper plot) and synthetic air (lower plot) atmospheres, both at gas flow rate of 0.5 L min^{-1} and heating rate of 10 °C min^{-1}.

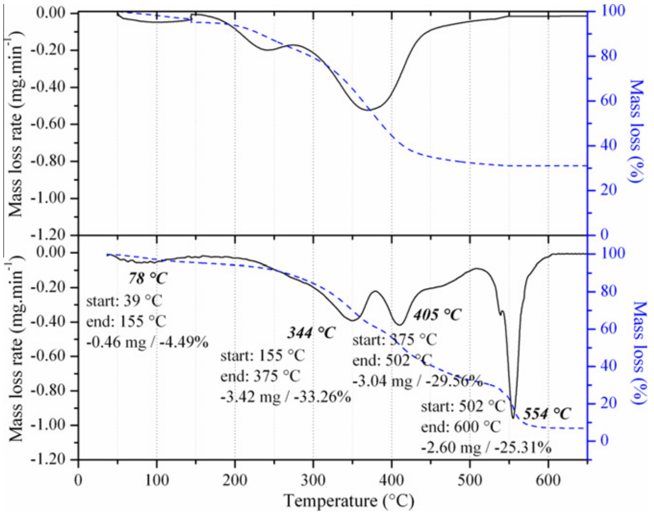

Fig. 2. TGA/DTG profiles of B1 in helium (upper plot) and synthetic air (lower plot) atmospheres, both at gas flow rate of 0.5 L min^{-1} and heating rate of 10 °C min^{-1}.

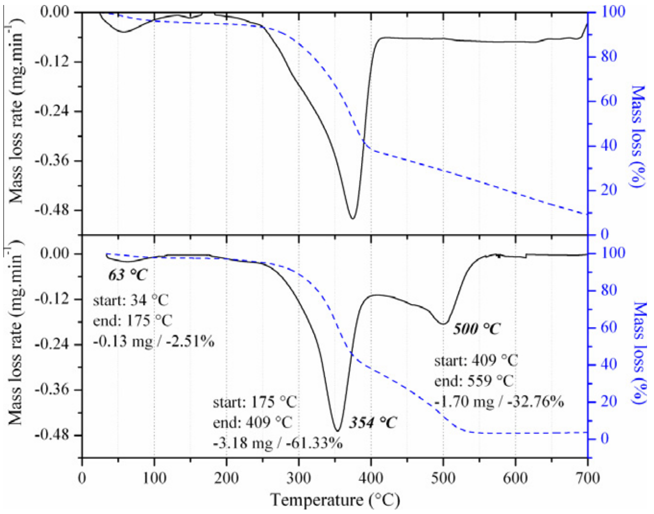

Fig. 3. TGA/DTG profiles of B1SD(1:9) in helium (upper plot) and synthetic air (lower plot) atmospheres, both at gas flow rate of 0.5 L min^{-1} and heating rate of 10 °C min^{-1}.

The faster volatilisation and burning of the wood sawdust fraction lead to higher mass loss rates in the first combustion stage of B1SD(1:9), in the temperature range from 200 °C to 400 °C, similarly to SD.

The TGA/DTG profile obtained for AB (Fig. 4) was slightly different from that observed for SD, with the fast burning region occurring between 450 °C and 530 °C, with the devolatilisation and degradation of the volatile matter fraction also appearing to occur simultaneously to the degradation of fixed carbon.

Table 2 presents the combustion parameters for all agroindustrial biomasses studied, which have been obtained by thermogravimetry.

The ignition temperatures were determined by comparison of the mass loss curves obtained from the analysis performed under inert and oxidising atmospheres, such as described in the experimental section. As suggested by Grotkjær et al. (2003), various parameters can influence the temperature and the ignition mechanism. These include the sample mass, the particle size (and even

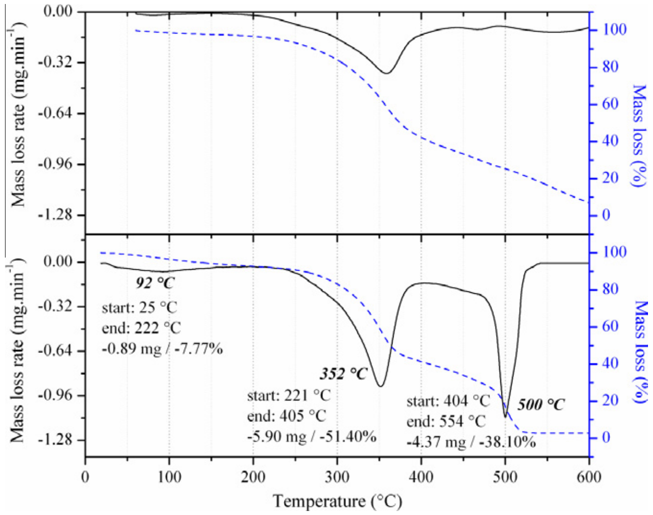

Fig. 4. TGA/DTG profiles of AB in helium (upper plot) and synthetic air (lower plot) atmospheres, both at gas flow rate of 0.5 L min^{-1} and heating rate of 10 °C min^{-1}.

its geometry), the volatile matter content, the sample devolatilisation extent and the oxygen concentration in the fuel as well as in the atmosphere composition. Besides these variables, the operating parameters of the conversion system can also be determinant.

Comparing the information obtained by TGA/DTG analysis for the different biomass samples, it was observed that the biosolids originating from the meat processing industry presented ignition temperatures varying from 124 °C to 168 °C, with the ignition of the sample OR also occurring in this range. The sample B2 presented the lower temperature in which the maximum mass loss rate occurred, which is an indicative of its higher reactivity. To the biomasses B1, SB, OR and AB, the peak temperatures were higher than 450 °C, thus occurring in the region of fixed carbon degradation and decomposition of different organic compounds.

The TGA/DTG data obtained from the biomass characterisation allowed a better understanding of initial and final biomass degradation temperatures and of biomass reactivity. The combustion behaviour observed through the thermogravimetric analysis was reproduced during a combustion tests performed with B1, such as described by Virmond et al. (2011), being helpful for the setting and adjustment of the process conditions, especially the combustion temperature which, on its turn, regulates the ash properties, as discussed in the next section. The more reactive the biomass, the lower the process temperature and the processing time required for complete conversion, what supports the control of the residence time and also contributes to minimising the ash relating problems in thermochemical conversion processes.

The homogeneity, particle size range and reactivity also influence the operation of the combustion process, especially in the case of the cyclone combustor studied by the authors in previous publications addressed in this paper, in which the biomass particles are burned in suspension. The feeding of pulverized biomass, for example, could result in very short residence times in the combustion zone, with incomplete burning. Based on that, the particle size ranged from 0.5 mm to 2 mm, approximately. In the case of the biosolids from the meat processing industry studied, the particle shape was granular due to the biomass characteristics and to the drying process previously performed in a rotating granulator dryer. The plant biomasses, given their fibrous nature, presented various shapes, such as SD and AB, but also in the referred particle size range. Besides particle size and shape, the moisture content of the biomasses has to be constrained to a defined range (typically from 10 wt.% to 30 wt.%) in order not to can cause ignition and combustion problems.

In the previously mentioned work, the combustion temperature range was defined, from 900 °C to 1100 °C, based mainly on the N and S contents found in the raw biomass and on the biomass ash properties. At temperatures lower than 900 °C, incomplete combustion would lead to high CO concentrations and on the formation of other pollutants, besides reduction of the process efficiency. On the other hand, at temperatures higher than 1100 °C both problems related to ash sintering in the thermal surfaces (such as depicted on the next section) and to the emission of NO_x could be aggravated.

Fluidised bed gasifiers usually operate at temperatures well below the ash fusion temperatures of the fuels (900–1050 °C) to avoid ash melting, constituting a promising processing option for most of the biomasses studied. A consequence of the low operating temperatures is the incomplete carbon conversion in a single stage and it is therefore common for the residual char to be either removed and burnt in a separate combustion unit (hybrid cycle) or recirculated into the gasifier (Collot, 2006).

3.1.3. Ash composition and ash fusibility trends

The composition of the ash samples, the ash fusibility temperatures and the values obtained from the selected ash fusibility correlations were presented in Table 3.

The biomass origin influences the fouling and slagging properties. Reports found in the literature have proposed that the combination of alkali metals and sulphur in these residues can promote ash fouling and slagging in the conversion systems, such as

Table 2
Parameters obtained by thermogravimetry.

Biomass	T_{ign}[a] (°C)	T_{max1}[b] (°C)	DTG_{max1}[c] (mg min^{-1})	T_{max2}[b] (°C)	DTG_{max2}[c] (mg min^{-1})	T_{max3}[b] (°C)	DTG_{max3}[c] (mg min^{-1})
B1	168	344	0.38	405	0.40	554	0.95
B2	124	220	0.10	330	0.26	488	0.09
B3	143	317	0.14	472	0.10	n.a.[d]	n.a.
B1SD(3:1)	160	270	0.56	343	0.71	487	0.23
B1SD(1:9)	250	354	0.47	500	0.18	n.a.	n.a.
B3SD(1:3)	145	345	0.32	489	0.10	545	0.03
SD	250	365	0.32	500	0.15	n.a.	n.a.
SB	255	357	1.16	475	2.02	n.a.	n.a.
AK	232	324	1.44	529	0.67	n.a.	n.a.
OR	147	242	0.46	338	0.38	468	0.89
AB	222	352	0.89	500	1.11	n.a.	n.a.
RH	177	336	0.33	477	0.15	n.a.	n.a.

[a] T_{ign}, Ignition temperature;
[b] T_{max}, Temperature in which occurs the maximum mass loss rate in oxidising atmosphere;
[c] DTG_{max}, Maximum mass loss rates observed at each temperature peak after sample ignition.
[d] Not applicable.

Table 3
Ash properties.

Biomass	B1	B2	B3	B1SD(3:1)	B1SD(1:9)	B3SD (1:3)	SD	SB	AK	OR	AB	RH
Ash composition[a] (wt.%, db[b])												
Fe_2O_3	32.40	21.89	35.50	20.95	7.24	5.39	4.44	0.47	0.13	2.91	5.92	0.25
CaO	17.40	8.36	8.25	10.02	29.88	3.92	31.27	6.17	5.65	22.22	13.44	0.70
MgO	1.30	n.d.[c]	0.91	2.37	10.61	0.83	11.64	8.00	6.82	6.34	8.98	0.61
Na_2O	1.70	n.d.	0.99	0.62	1.67	0.43	1.67	0.45	1.18	0.26	0.93	n.d.
K_2O	1.70	1.70	0.98	3.30	9.57	0.82	10.44	23.42	30.15	31.58	31.27	1.06
SiO_2	4.90	45.34	12.60	14.92	14.61	15.90	15.69	48.74	24.38	3.18	6.58	94.87
Al_2O_3	1.70	n.d.	3.72	18.23	11.24	3.66	12.30	2.42	0.31	2.54	2.65	0.84
TiO_2	<0.30	0.48	0.30	0.38	3.55	0.17	3.94	0.16	0.04	0.19	2.48	0.03
P_2O_5	36.30	20.51	33.60	26.88	6.10	15.60	2.74	6.91	24.53	10.71	18.52	1.25
MnO	n.d.	0.29	0.20	0.43	1.85	0.04	2.06	0.12	2.66	0.10	0.24	0.21
SO_4	n.d.	n.d.	0.25	1.90	2.72	2.76	3.02	3.14	4.15	3.42	3.44	n.d.
CuO	n.d.	0.38	0.14	n.d.	n.d.	0.02	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
ZnO	n.d.	0.16	0.59	n.d.	n.d.	0.02	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Cr_2O_3	n.d.	0.09	0.10	n.d.	n.d.	0.08	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Co_3O_4	n.d.	n.d.	0.06	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
NiO	n.d.	0.69	0.11	n.d.	n.d.	0.01	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Rb_2O	n.d.	n.d.	<0.01	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
SrO	n.d.	0.09	0.03	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
ZrO_2	n.d.	0.03	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
BaO	n.d.	n.d.	0.07	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
PbO	n.d.	n.d.	0.01	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
PF	2.60	n.d.	1.59	n.d.	0.97	50.35	0.79	n.d.	n.d.	n.d.	n.d.	n.d.
Ash fusibility temperatures (°C)												
Deformation	750	n.d.	n.d.	n.d.	n.d.	n.d.	>1150[d]	n.d.	n.d.	n.d.	n.d.	n.d.
Softening	990	n.d.	n.d.	n.d.	n.d.	n.d.	>1170[d]	n.d.	n.d.	n.d.	n.d.	n.d.
Hemispherical	1010	n.d.	n.d.	n.d.	n.d.	n.d.	>1190[d]	n.d.	n.d.	n.d.	n.d.	n.d.
Fluid	1040	n.d.	n.d.	n.d.	n.d.	n.d.	>1230[d]	n.d.	n.d.	n.d.	n.d.	n.d.
Ash fusibility correlations												
$B/A_{(+P)}$	13.76	1.14	4.83	1.91	2.21	1.37	1.95	0.89	2.77	12.52	6.75	0.04
$R_{S(+P)}$	4.13	0.00	0.00	1.15	0.07	0.00	0.00	0.00	2.35	1.75	0.00	0.00

[a] Maximum experimental uncertainties equal to 0.30%.
[b] Dry basis.
[c] Not determined.
[d] Data from Llorente and García (2005), for Eucalyptus I sample.

predicted through the ash fusibility correlation $R_{S(+P)}$. The presence of phosphorus in the form of P_2O_5 is also related to these problems, and was taken into account in the correlation $B/A_{(+P)}$ presented in Table 3. For the biomasses whose calculated values for the fusibility correlations $B/A_{(+P)}$ and $R_{S(+P)}$ were high (higher than 2.6 in the case of $R_{S(+P)}$, the reference value for this index), the tendency toward fouling and slagging is extremely high.

The dominant features of wood ash are its very high calcium content and the absence of sulphur. Additionally, it is rich in acid oxides (SiO_2, Al_2O_3, TiO_2). The lowest value for the ratio of basic to acid oxides ($B/A_{(+P)}$) and the zero value for $R_{S(+P)}$ indicate that the melting temperature of SD ash is high, which was previously reported by Llorente and García (2005) and presented for SD in Table 3. In the case of wood, even if formed on radiation surfaces, the deposits will be loose (Pronobis, 2005).

The ashes of the meat processing residues (B1, B2 and B3) are rich in iron, phosphorus and calcium, besides the presence of sulphur in the raw fuel. The sample B3 presented relatively lower value of $B/A_{(+P)}$ due to the higher concentration of SiO_2.

In the case of B1, $B/A_{(+P)}$ was 13.76, value much higher than the value found for SD (0.00) and for coal (0.28), the latter reported by Bryant et al. (2000). This tendency has been confirmed by the low fusibility temperatures determined for B1 ash, which becomes fluid at 1040 °C, temperature 360 °C lower than the fluid temperature of SD.

As mentioned before, the coagulant agent applied to the physicochemical treatment of the meat processing wastewater is of primary importance in terms of the biomass and ash compositions. The utilisation of $Fe_2(SO_4)_3$ in the physicochemical wastewater treatment which originates B1 modifies the base-to-acid $B/A_{(+P)}$ ratio due to an increase in the Fe_2O_3 concentration in the ash, favouring its agglomeration. The substitution of this coagulant for aluminium sulphate $Al_2(SO_4)_3$, for example, would reduce the value of the $B/A_{(+P)}$ index of B1 in particular, and therefore minimise the agglomeration problems when pure B1 is burned. In the combustion system studied by Virmond et al. (2011), even considering the short residence time of the B1 biomass inside the combustion chamber due to the high velocity promoted by the cyclone, the occurrence of these problems was still observed due to the high combustion temperature and to the low ash melting temperature.

From the values of $B/A_{(+P)}$ and $R_{S(+P)}$ obtained to B1SD(1:9) and B3SD(1:3), it can be inferred that blending SD with meat processing industry residues may produce minerals with much higher melting temperatures and the fouling tendency would decrease compared to the use of pure residues. However, it requires further investigation to determine the influence of different mixture ratios for co-combustion or gasification application. Thus, the selection of the reactor configuration relating the flow geometry to the biomass properties is mandatory.

Besides emission related concerns, chlorine also plays a role on ash fusibility given that it facilitates the mobility of some inorganic compounds, such as potassium, which can form inorganic mixtures with silicon and reduce the fluid temperature from approximately 1700 °C (silicon melting point) to about 750 °C (Llorente et al., 2006).

Amongst the biomasses studied, it has been observed that $B/A_{(+P)}$ and $R_{S(+P)}$ values were high to the samples of *açaí* kernels (AK), orange juice residues (OR) and apple juice residues (AB), mainly due to the higher concentration of alkaline metal oxides such as K_2O, alkaline-earth metal oxides such as CaO and MgO, and also P_2O_5, constituents which are commonly associated to the ash fusibility behaviour in the case of plant biomasses.

Alkali metals, such as potassium, react readily with silica, even at temperatures far below 900 °C, by breaking the Si–O–Si bond and forming silicates or reacting with sulphur to produce alkali sulphates. The alkali silicates and sulphates have melting points even lower than 700 °C and tend to deposit on the reactor walls and leave a sticky deposit on the surface of the bed particles, causing bed sintering and defluidisation (Arvelakis et al., 2002, 2005). Furthermore, the presence of ash such as alkali in syngas can cause problems of deposition, corrosion and erosion for equipment that utilises syngas such as a gas turbine (Wang et al., 2008).

Even though presenting an interesting energy content and low values for the fusibility indexes, the direct combustion of rice husk (RH) shall not be performed if an efficient system for retention of the particulate matter rich in silicon oxides (94.87 wt.% SiO_2 in the ash, db), characteristic of this biomass, is not available to avoid potential health problems related to their emissions. Alternatively, other thermochemical conversion processes could be applied to this residue, such as pyrolysis and gasification.

Considering the existing commercial gasifier configurations, Gabra et al. (2001) stated that fluidised bed gasification performs better than fixed bed gasification to reduce ash-related problems since the bed temperature of fluidized bed gasification can be kept uniformly below the ash slagging temperature. This would favour the conversion of the pure organic solid residue originating from the meat processing industry, for example. The low gasification temperature can also reduce the volatilisation of ash elements such as sodium and potassium into the syngas, thus improving the quality of syngas.

On the other hand, some technologies are meant to work with the removal of the ash fraction in the sintered form. For the case of coal gasification, Collot (2006) describe that all entrained flow gasifiers are slagging gasifiers and each technology has slightly different requirements for coal properties depending on the design. The same may apply to biomass. There is a minimum ash content required for gasifiers with slag self-coating walls which have to be covered by slag to function and minimise heat loss through the wall. A maximum ash content is also usually fixed for each type of entrained flow gasifier as the tolerance to ash content depends on economic and technical factors. Leaching and fractionation are the two main pre-treatments used to reduce ash-related problems (Arvelakis et al., 2002, 2005; Arvelakis and Koukios, 2002), and can constitute an option to improve biomass thermochemical conversion. Some findings have shown that mechanical fractionation could reduce up to 50% of the ash in the biomass but the remaining ash still causes the ash related problems at a high temperature (Arvelakis et al., 2002, 2005).

4. Conclusions

Increasing the use of agroindustrial solid residues as substitute and alternative fuels in thermochemical processes constitutes an effective option to reduce energy costs in the Brazilian agroindustry and the environmental problems associated with waste disposal.

The evaluation of the biomass properties constitutes the initial step in defining the thermochemical process to be applied. Based on that, the potential for application of the Brazilian agroindustrial solid residues studied as alternative energy sources in thermochemical processes has been identified, especially concerning direct combustion for steam generation and gasification.

The investigated agroindustrial biomasses presented high energy contents, ranging from 14.31 MJ kg^{-1} to 29.14 MJ kg^{-1} (daf), all presenting high volatile matter content varying between 70.57 wt.% and 85.36 wt.% (daf). The biosolids originating from the meat processing industry (B1, B2, B3) presented higher calorific values comparatively to the other residues due to the combination of high contents of C, H and volatile matter with the high grease content.

The additives applied to meat processing operations, the degradation of proteins as well as the chemicals applied to the physicochemical treatment of the industrial effluent influence the biomass composition and have to be taken into consideration for biofuel application, especially concerning the emission of N, S and Cl derived compounds during thermal processing. An option to minimise problems related to the presence of such elements is to previously treat the biomass for removal of contaminants through fractionation or leaching, for example, or to blend residues with sawdust (extensively used as fuel for thermal energy generation in the Brazilian industrial sector) in low mass ratios. This can reduce the N, S and Cl contents due to the dilution effect, thus increasing its energetic exploitation potential in co-combustion processes due to the potentially lower pollutants emission in relation to the burning of the pure biomasses. Additionally, the reduction of the ash content with the blending would consequently reduce the problems which may arise due to the ashes fusibility behaviour. Alternatively, gasification of the biomasses with some of these characteristics may be the most feasible thermochemical conversion option.

Concerning the ash composition, the application of ash fusibility correlations to predict the degree of biomass ash fouling and slagging during thermochemical conversion can aid to avoid the occurrence of operating problems in the industrial application of such residues in pyrolysis, combustion and gasification processes.

The initial combustion parameters such as moisture content, A/F ratio and combustion temperature which have been applied to operating the combustion tests performed by the research group with some of these biomasses were defined based on the results presented in this study.

Given that rice husk is an important agroindustrial solid residue in Brazil, besides its potential application to combustion, the authors have been conducting a complementary study in which the gasification potential of rice husk is being assessed through the evaluation of the effects of the pyrolysis step on char formation, structure, composition and reactivity in synthetic air and in CO_2 with the aim to provide a feasible alternative for its thermochemical conversion.

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